90 YEARS

PERIODICAL FIELD DEPENDENCE OF MAGNETIC SUSCEPTIBILITY OF METALS AT LOW TEMPERATURES

Translated and reprinted from Zh. Eksp. Teor. Fiz. **20**, No. 1, pp. 93–94 (1950)

B.I. VERKIN, B.G. LAZAREV, N.S. RUDENKO

Physico-Technical Institute, Academy of Sciences of the Ukrainian SSR
(Kharkov, Ukraine)

Ii was considered many years that the periodic dependences of electric resistance (Shubnikov-de Haas effect [1]) and magnetic susceptibility (de Haas-van Alphen effect) observed in Bi single crystals at low temperatures were anomalous properties unique to this metal. However, in 1939, Lazarev, Nakhimovich, and Parfenova [3] discovered the Shubnikov-de Haas effect in Zn single crystals; in 1949, Borovik, a collaborator of our laboratory, detected this effect in Sn single crystals [4]. We believed that the two effects are common to all metals though the conditions for their manifestation are peculiar to each metal. Systematic investigations of the magnetic properties of metals at low temperatures were started to prove this viewpoint.

The investigation technique consisted in measuring the couple of forces acting upon the crystal suspended with a thin elastic filament in a homogeneous magnetic field [5]. The highest-symmetry axis of the crystal was in the plane of the field, i.e. perpendicularly to the suspension axis. The difference between the susceptibilities along and perpendicularly to the symmetry axis was measured by the twisting angle of a filament. The measurement temperatures were 78, 20, and 14 K and down to 2 K (helium temperatures). The field varied from 4000 to 14000 Oe.

Zinc was the first object of investigation. The de Haas-van Alphen effect was detected in it even at the liquid hydrogen temperature. By this time, Sidoriak et al. had also investigated this phenomenon in Zn [6]. Later on, we revealed the de Haas-van Alphen effect in Sn [7]. This was followed by investigations of single crystals of Be, Mg, In, and, finally, Cd. All of these metals exhibited a periodic dependence of the magnetic susceptibility on the magnetic field.

In Be, the effect is evident at $T = 20.4$ K, enhances at the liquid helium temperature, and is well measurable in much lower fields. In a field of 5000 Oe, the dependence of the difference of susceptibilities in Be oscillates with a period of 180 Oe which increases to 1000 Oe in the field of 12000 Oe.

In Mg, the phenomenon is observable distinctly at $T = 4.2$ K and enhances considerably with a further lowering of the temperature. In a field of 10000 Oe, the oscillation period of the difference of susceptibilities for a Mg single crystal is 140 Oe and increases to 280 Oe in a field of 14000 Oe.

In indium, the effect appears at $T \sim 2$ K in a field over 13000 Oe.

Cd exhibits this effect at temperatures below 2 K in high fields. The oscillation period is ~ 25 Oe in a field of 12000 Oe and increases to 40 Oe in a field of 14000 Oe. It is worth to mention that we turned to Cd after having detected the de Haas-van Alphen effect in Zn. Our further searching was therefore much guided by the similarity of the electric resistance behavior in a magnetic field that we had noticed in these single crystals with identical crystallographic orientations [3]. Although these metals have identical crystal lattices, the characteristic temperature of Cd is lower, and the de Haas-van Alphen effect shows up in it at lower temperature than that in Zn.

In the diagram showing the couple of forces versus the angle of the field direction with the principal crystallographic axis of the single crystal, the anomaly of susceptibility reveals itself as a complicated angular dependence of the measured couple of forces.

We observed the de Haas-van Alphen effect in Sn almost at the same time as Shoenberg did, who detected it also in Ga and graphite [8].

At present, the periodic character of the dependence of susceptibility on the magnetic field at low temperatures is known for Bi, Zn, Sn, Be, Mg, In, Cd, Ga, and graphite. These results allow us to conclude that the de Haas-van Alphen effect is quite a common property of metals rather than an anomalous phenomenon. This conclusion conforms to theoretical works concerning this effect [9]. The existence of the effect only at rather low temperatures in high fields and its small oscillation period in some metals explain why many researchers had negative results of the searching for the effect even in metals where it is quite pronounced, for example, in Cd, In, Mg, and Sn [3, 8, 10].

1. L. Schubnikow, W.J. de Haas, Leid. Comm., N 207d, N 210a (1930).
2. W.J. de Haas, P. M. v. Alphen, Leid. Comm., N 212a (1930), N 220d (1932).
3. B.G. Lazarev, N.M. Nakhimovich, E.A. Parfenova, Zh. Eksp. Teor. Fiz. **9**, 1169, 1182 (1939); N.M. Nakhimovich, Journ. of Phys. **5**, 141 (1941).
4. E.S. Borovik, Dokl. Akad. Nauk USSR **69**, 767 (1949).
5. D. Shoenberg, Zh. Eksp. Teor. Fiz. **8**, 1271 (1938); D. Shoenberg and Zaki Uddin, Proc. Roy. Soc. A **156**, 701 (1936); D. Shoenberg, Proc. Roy. Soc. A **170**, 341 (1939).
6. S. Sydoriak, J. Robinson, Phys. Rev. **75**, 118 (1949); J. Marcus, Phys. Rev. **71**, 559 (1947); L. Mackinon, Proc. Roy. Soc. **62**, 170 (1949).
7. B. Verkin, B. Lazarev, N. Rudenko, Usp. Fiz. Nauk **39**, 319 (1949).
8. D. Shoenberg, Nature **164**, 225 (1949).
9. R. Peierls, Zs. f. Phys. **81**, 186 (1938); M. Blackmail, Proc. Roy. Soc. A **166**, 1 (1938); L.D. Landau, Proc. Roy. Soc. A **170**, 341 (1939) (theoretical part of D. Shoenberg's work); A.I. Akhiezer, Dokl. Akad. Nauk USSR **23**, 872 (1939); Yu.B. Rumer, Zh. Eksp. Teor. Fiz. **18**, 1081 (1948).
10. T. McQuire, Phys. Rev. **76**, 167 (1949).

Received November 11, 1949

VERKIN BORIS IEREMIEVICH
(8.08.1919–12.06.1990)

Boris Ieremievich Verkin was an outstanding physicist, Full Member of NAS of Ukraine, an organizer and the first Director of the Institute for Low Temperature Physics and Engineering of the NAS of Ukraine. His scientific studies are concerned with physics and engineering at low temperatures, the electronic and magnetic properties of solids, superconductivity, low-temperature materials science. The presented paper was the first brief report informing about low-temperature oscillations of susceptibility in a number of metals. The paper was a worthy continuation of the scientific trend pioneered by L.V. Shubnikov. The results reported have become the academic classics of many manuals and monographs on the electronic and magnetic properties of metals. The material concerned is detailed in Zh. Eksp. Teor. Fiz. **20**, 995 (1950).

LAZAREV BORIS GEORGIEVICH
(06.08.1906–20.03.2001)

Boris Georgievich Lazarev was the outstanding physicist-experimentalist, Full Member of the National Academy of Sciences (NAS) of Ukraine (1951), winner of the State prize of the USSR (1951) and UkrSSR (1982). He was born in the Myropol'e village (now the Sumy region) in Ukraine. From 1928 till 1932, B.G. Lazarev had worked at the Leningrad Physical-Technical Institute, then he had worked at the Ukrainian Physical-Technical Institute (now National Science Center "Kharkov Institute of Physics and Technology" of NAS of Ukraine) from 1937 till 2001. He was Head of a laboratory at UPhTI (after L.V. Shubnikov, 1938) and Head of a department of KIPT (till 1988). B.G. Lazarev and his colleagues carried out a series of works concerned with the electronic properties of metals, liquid helium properties, cryogenic technique for the creation of high vacuum. He had proposed and realized the method of helium isotope separation (1950) [1], discovered the (2+1/2)-phase transition (1963), had measured the magnetic moment of a proton in solid hydrogen (together with L.V. Shubnikov, 1936), quantum oscillations of the magnetic susceptibility for a number of metals at low temperatures [2]. B.G. Lazarev is a founder of the scientific school in low-temperature physics.

1. B.N. Eselson and B.G. Lazarev, Zh. Eksp. Teor. Fiz. **20**, 742 (1950).
2. B.I. Verkin, B.G. Lazarev, and N.S. Rudenko, Zh. Eksp. Teor. Fiz. **20**, 995 (1950).